DEVELOPMENT HEAT TRANSFER CORRELATIONS FOR SUPERCRITICAL CO_2 IN NATURAL CIRCULATION LOOP

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ABSTRACT

Supercritical CO_2 has been receiving growing attention as a fluid for heat transfer and been proposed for various industrial applications, due to its favourable physical and chemical properties. This paper presents an analysis of three newly developed heat transfer correlations for supercritical CO_2 in natural circulation. Heat transfer experiments were conducted in a rectangular natural circulation loop with bulk fluid temperature from 21 to 189 ℃, pressures from 7.45 to 8.90 MPa, local wall heat fluxes from 10.5 to 96.0 kW/m^2, and mass fluxes form 235 to 480 kg/m^2/s. Based on experimental data, three correlations were developed based on different qualitative temperatures. The performance of classical correlations was also analyzed.

Distributions of wall temperature and heat transfer coefficient were significantly affected by heat flux. With the increase of heat flux, noticeable peak of wall temperature would occur at the upstream of the test section and gradually moved closer to the inlet of the heating section. These classical heat transfer correlations for supercritical fluids could not accurately predict the heat transfer characteristics of supercritical carbon dioxide in natural circulation and most of them distinctly overestimated the heat transfer of supercritical carbon dioxide in natural circulation, especially in heat transfer deterioration region and heat transfer enhancement region. The predictions of these newly developed correlations agreed well with experimental data. Among them, the correlation using bulk temperature as qualitative temperature showed the best performance.

KEYWORDS

Supercritical carbon dioxide, natural circulation, heat transfer correlation, buoyancy

1. INTRODUCTION

Due to its favourable physical and chemical properties, supercritical CO_2 has been receiving growing attention as a fluid for heat transfer and been proposed for various industrial applications[1-2]. The heat transfer characteristics of supercritical CO_2 are crucial for the design of these systems, which are obviously different from subcritical fluid due to the significant change of thermal properties near the critical point (see Fig. 1).

Wood and Smith [3] found that the maximum of velocity could be at a radial position away from the center of the tube. Hall [4] found that the turbulent diffusivity was reduced in upward flow when the low density layer became thick enough to reduce the shear stress in the region where energy was fed into the turbulence, which reduced the diffusivity for heat in supercritical pressure. Kurganov and Kaptil'nyi [5] studied the velocity and eddy diffusivities in a heated supercritical CO_2 flow, and found the M-shaped velocity profiles in the upward flow in HTD conditions. Bazargan and Mohseni [6] reported that the peak of heat transfer coefficient (HTC) occurred when the pseudo-critical temperature was located in the buffer layer. They also reported that the buffer zone was farther away from the wall due to the increase of the extent of laminar sub-layer in the HTD conditions. Bae et al. [7] found that the Nusselt number decreased significantly before the HTD regime and the deterioration criterion based on the buoyancy parameter performed very well in their experiments.

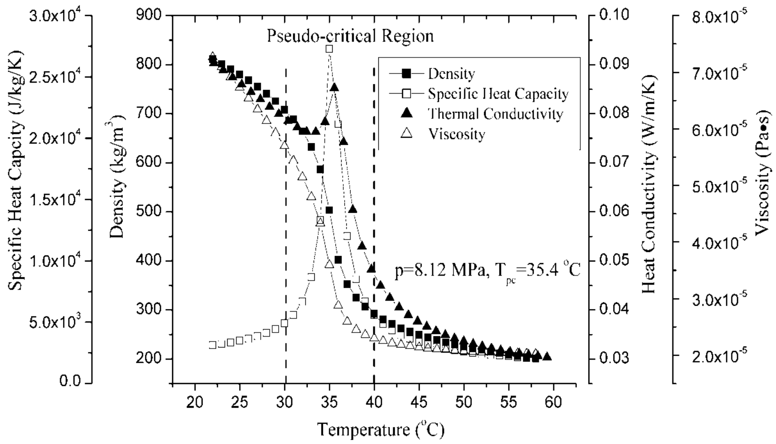

Fig. 1 Variation of thermal properties of CO_2 with temperature at different pressures

However, most of these studies focused on the heat transfer of supercritical CO_2 in forced circulation loop, and few works were performed for heat transfer in natural circulation loop. Different driving mechanisms would result in different flow fields between the natural circulation and forced circulation [8]. Besides, the sharp change of thermal properties may strengthen the difference. Existing correlations for supercritical CO_2 are mainly based on experimental data obtained in forced circulation, developing heat transfer correlations for natural circulation is quite necessary.
In this study, three heat transfer correlations for supercritical CO_2 natural circulation were developed based on different qualitative temperatures and their predictions were compared with typical heat transfer correlations.

2. Experimental apparatus
2.1. Experimental Loop

Fig. 2 shows a schematic diagram of the natural circulation loop in Nuclear Power Institute of China (NPIC). The heating section of the loop was constructed from an INCONEL 625 tube with an internal diameter of 6-mm. The total length of the heating section was 2410-mm. The heating section was heated electrically using a DC power supply (20 V, 1000 A, 20 kW) to provide a uniform heat generation rate.

The inlet and outlet temperatures of the heating section were measured by platinum resistance thermometers. The outside wall temperatures were measured by thermocouples (1-mm diameter) brazed on the outer surface of the heating section. The mass flow rate was measured by a Venturi meter, which has a measure range from 10 to 100 kg/h. The purity of CO_2 used in experiments was 99.95%. Table 1 shows the ranges of instruments and theirs accuracies.

Table 1 ranges and uncertainties of primary parameters

Instrument	Range	Uncertainty
platinum resistance thermometer	0-300℃	±0.3%
Thermocouple	0-400℃	±0.4%
Test-section power	0-5kW	±0.6%
Mass flow meter	10-100kg/h	±1.5%
Pressure transmitter	0.1-20.7MPa	±0.2%

2.2. Experimental conditions

The major parameters in experiments were heat flux (q), fluid temperature (T_b), inside wall temperature ($T_{w,in}$), mass flux (G), system pressure (p), Reynolds number (Re_b) and Prandtl number (Pr_b). The values of these parameters had the following ranges: q: 10.5-96.0 kW/m^2, T_b: 21-189 ℃, $T_{w,in}$: 28-296 ℃, G: 235-480 $kg/m^2/s$, p:7.45 MPa (1.01 p_c), 8.12 MPa (1.1 p_c), 8.90 MPa (1.2 p_c).

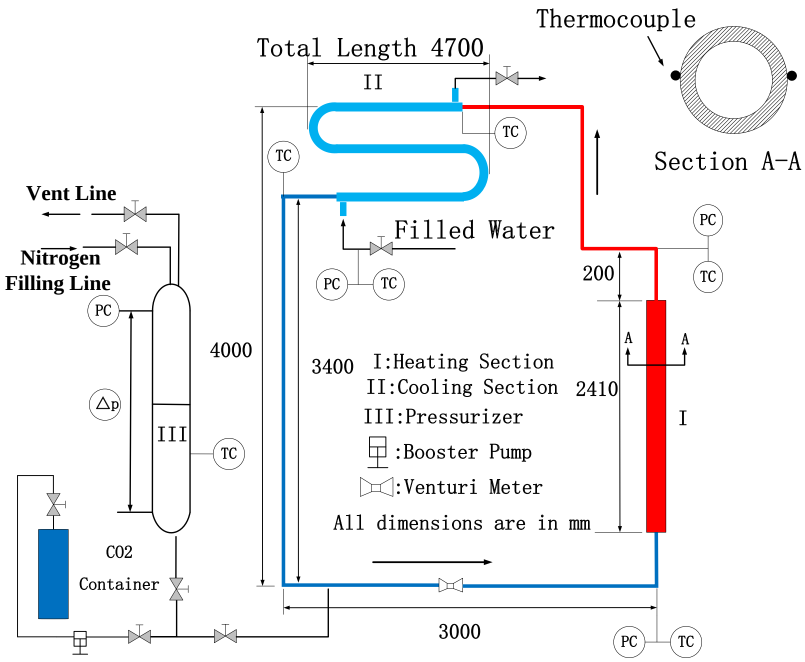

Fig. 2. Schematic diagram of supercritical natural circulation loop in NPIC

3. Experimental results and discussion

3.1. General trends

At the entrance region, HTC decreased along the test section due to the development of the thermal-boundary-layer in that region. With medium heat flux, the HTC increased sharply when the bulk temperature got close to the pseudo-critical temperature, and the HTC took a maximum at a bulk temperature which was slightly lower than the pseudo-critical temperature (see Fig. 3).

At relatively high heat flux, noticeable heat transfer deterioration (HTD), characterized by much higher value of wall temperature, would occur at the upstream of the heating section. With the increase of heat flux, the heat transfer deterioration became more obvious and the point of deterioration gradually moved closer to the inlet of heating section. Buoyancy and flow acceleration are the two main reasons for the heat transfer deterioration in supercritical pressures conditions, and the former one is the main reason in relatively low mass flux condition. It can be observed from Fig. 4 that the heat transfer deterioration was corresponded with the maximum of buoyancy force. So buoyancy force has vital effect on the heat transfer of supercritical carbon dioxide in natural circulation condition, which should be taken into consideration in heat transfer correlation.

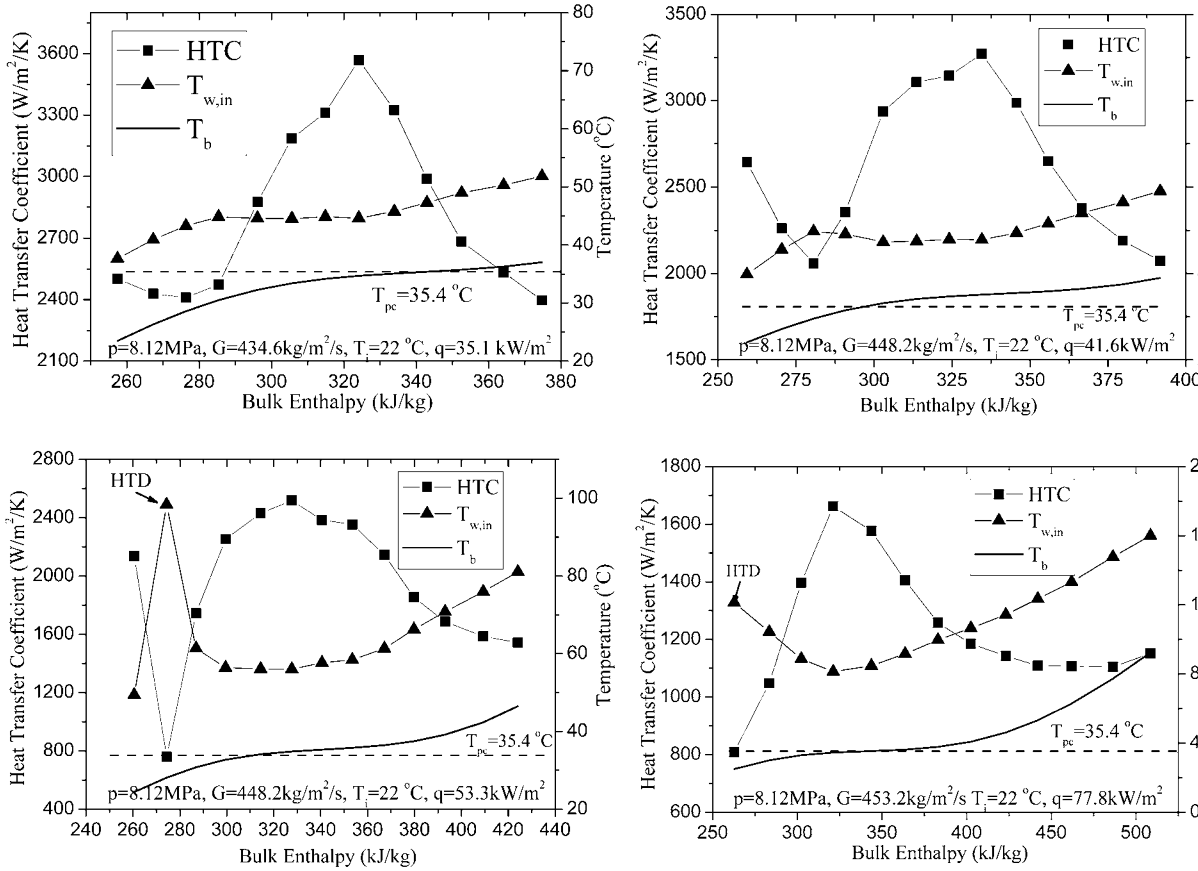

Fig. 3. Variation of temperature and HTC with bulk enthalpy

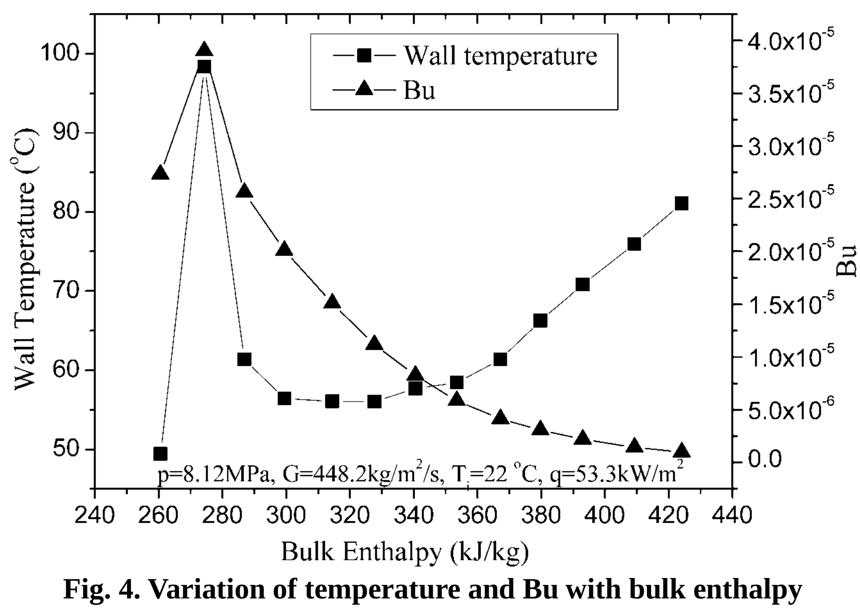

Fig. 4. Variation of temperature and Bu with bulk enthalpy

3.2. Classical correlations

Researchers have proposed many heat-transfer correlations for supercritical fluids based on their experimental results. However, these correlations were very similar to each other, which used classical equation for constant property condition in conjunction with the various property correction terms. Krasnoshchekov correlation [9] (see Eq. (1)), Jackson correlation [10] (see Eq. (2)), Mokry correlation [11] (Eq. (3), and Bishop correlation [13] (see Eq. (4)) are typical representatives.

$$Nu = \frac{f/8 Re_b \overline{Pr}}{12.7(\sqrt{f/8}(Pr^{2/3}-1)+1.07}(\frac{\rho_w}{\rho_b})^{0.3}(\frac{\overline{c_p}}{c_{p,b}})^n \tag{1}$$

$$Nu = 0.0183 Re_b^{0.82} Pr_b^{0.5}(\frac{\rho_w}{\rho_b})^{0.3}(\frac{\overline{c_p}}{c_{p,b}})^n \tag{2}$$

where n=0.4 for $T_b<T_w<T_{pc}$, $1.2T_{pc}<T_b<T_w$; n=0.4+0.2[(T_w/T_{pc})-1] for $T_b<T_{pc}<T_w$; n=0.4+0.2[(T_w/T_{pc})-1]{1-5[(T_b/T_{pc})-1]}, for $T_{pc}<T_b<1.2T_{pc}$, $T_b<T_w$; T_b, T_w, T_{pc} are in K.

Eq. (1) is valid within the following ranges: $8\times10^4<Re_b<5\times10^5$, $0.85<\overline{Pr}<65$, $0.09<(\rho_w/\rho_b)<1.0$, $0.02<(\overline{c_p}/c_{pb})<0.4$, 46<q<260 kW/m^2.

$$Nu = 0.0061 Re_b^{0.904}\overline{Pr}_b^{0.684}(\frac{\rho_w}{\rho_b})^{0.564} \tag{3}$$

$$Nu = 0.0069 Re_b^{0.9}\overline{Pr}_b^{0.66}(\frac{\rho_w}{\rho_b})^{0.43}(1+2.4\frac{D}{x}) \tag{4}$$

Eq. (4) is valid within the following ranges: 22.8<p<27.6MPa, $282<T_b<527$℃, 651<G<3662kg/m^2/s, 310<q<3460 kW/m^2.

3.3. Developing a new correlation

Dimensional analysis was performed to obtain the general empirical form of heat-transfer correlation. The Buckingham π-Theorem was used to formulate the following expression for heat transfer of supercritical CO_2 in natural circulation.

$$HTC = f(D_{in}, v, \rho_{w,in}, \rho_b, k_{w,in}, k_b, \mu_{w,in}, \mu_b, \overline{c_p}, c_{p,b}) \tag{5}$$

As a result of experimental data analysis, new heat-transfer correlations for supercritical CO2 in natural circulation, which took the effect of buoyancy on heat transfer into consideration, were obtained:
Bulk-Fluid-Temperature Approach

$$Nu = 0.0025 Re_b^{0.959} Pr_b^{0.56}(\frac{\rho_{w,in}}{\rho_b})^{0.57}(\frac{\lambda_{w,in}}{\lambda_b})^{-0.144}(\frac{\overline{c_p}}{c_b})^{0.628} Bu^{-0.025} \tag{6}$$

Film-Fluid-Temperature Approach

$$Nu = 0.0024 Re_f^{1.13} Pr_f^{0.31}(\frac{\rho_{w,in}}{\rho_b})^{1.37}(\frac{\lambda_{w,in}}{\lambda_b})^{0.49}(\frac{\mu_w}{\mu_b})^{-0.65} Bu^{0.085} \tag{7}$$

Wall-Temperature Approach

$$Nu = 0.0013 Re_w^{1.45} Pr_f^{-0.047} (\frac{\rho_{w,in}}{\rho_b})^{1.82} (\frac{\lambda_{w,in}}{\lambda_b})^{0.071} (\frac{\overline{c_p}}{c_{p,b}})^{0.19} Bu^{0.29} \quad (8)$$

The prediction performance of these correlations was evaluated as defined by Eqs. (6)-(8). Results were shown in table 2. The positive value of the mean error implied that the correlation overestimated the heat transfer performance of supercritical CO_2 in natural circulation. It can be observed from table 2 that the performance of Eq. (6) based on the bulk-fluid-temperature approach was the best among these newly developed correlations. 95.2% of experimental data predicted by the newly developed correlation (Eq. (6)) was within ±20% error bound, while the results of Mokry, Krasnoshchekov, Bishop, Jackson, Gupta correlation were 65.5%, 46.5%, 41.1%, 35.2%, and 31.8%, respectively. According to the table 2, the newly developed correlation (Eq. (6)) showed the best prediction performance.

Table 2 Mean error and RMS error for selected correlations from experimental results and the percentage of the data points within special error bounds

Correlations	**Mean error**	**RMS error**	**10%**	**20%**	**30%**
Mokry et al.	7.8	30.5	41.8	65.5	76.0
Krasnoshchekov et al.	28.1	38.5	23.9	45.6	63.1
Bishop et al.	26.8	34.3	18.8	41.1	63.8
Jackson	35.7	47.6	9.1	35.2	55.4
New correlation (Eq. (6))	**-3.0**	**10.6**	78.9	95.2	99.1
New correlation (Eq. (7))	7.1	15.5	63.9	82.6	92.3
New correlation (Eq. (8))	10.6	19.5	38.5	71.6	83.2

Fig. 5 shows the comparison of calculated Nu of different correlations with experimental ones. It can be observed from Fig. 5 that most of these correlations overestimated the Nu, especially in heat transfer deterioration and heat transfer enhancement region. The performance of Mokry correlation was relatively better and the newly developed correlation showed the best performance.

$$error = \frac{Nu_{cal} - Nu_{exp}}{Nu_{exp}} \quad (9)$$

$$Mean\ error = \frac{\sum_{i=1}^{i=n} error_i}{n} \times 100\% \quad (10)$$

$$RMS\ error = \sqrt{\frac{\sum_{i=1}^{i=n} error_i^2}{n}} \times 100\% \quad (11)$$

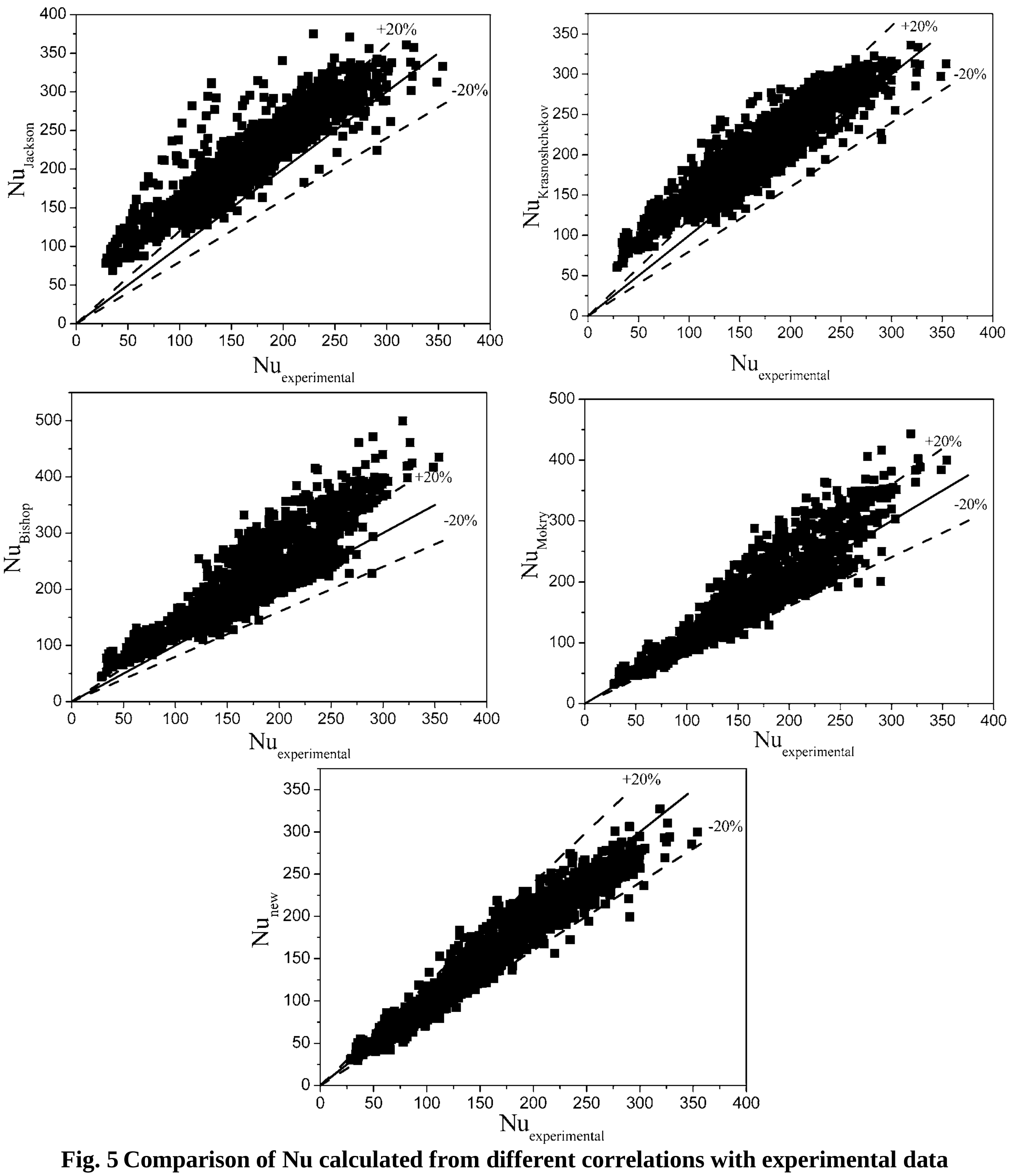

Fig. 5 Comparison of Nu calculated from different correlations with experimental data

4. CONCLUSIONS

Heat transfer experiments were conducted in a rectangular natural circulation loop. Three new heat transfer correlations based on different qualitative temperatures for supercritical CO_2 in natural circulation were developed. The performance of typical correlations was also analyzed.

Under our experimental conditions, the distributions of wall temperature and heat transfer coefficient were significantly affected by heat flux. With the increase of heat flux, noticeable peak of wall temperature would occur at the upstream of the test section and gradually moved close to the inlet of the heating section. The performance of these typical heat transfer correlations was not so well for supercritical carbon dioxide in natural circulation and most of them distinctly overestimated the heat transfer of supercritical carbon dioxide in natural circulation, especially in heat transfer deterioration region and heat transfer enhancement region. The prediction of these newly developed correlations agreed well with experimental ones. Among them, the correlation using bulk temperature as qualitative temperature showed the best performance.

NOMENCLATURE

Bu	Buoyancy parameter; $\overline{Gr_b} / Re_b^{2.7}(\mu_w / \mu_b)(\rho_w / \rho_b)^{-0.5}$
c_p	specific heat capacity, kJ/kg/K
$\overline{c_p}$	average specific heat capacity, kJ/kg/K; $(h_w-h_b)/(T_w-T_b)$
G	mass flux, kg/m^2/s
$\overline{Gr_b}$	Grashof number based on density; $\rho_b(\rho_b - \overline{\rho})gD_i^3 / \mu_b^2$
h	enthalpy, J/kg/K
k	thermal conductivity, W/m/K
L	length, m
m	mass flow rate, kg/s
Nu	Nusselt number; $HTC \cdot D / \lambda$
p	pressure, MPa
Pr	Prandtl number; $\mu c_p / \lambda$
$\overline{Pr}$	average Prandtl number; $\mu\overline{c_p} / \lambda$
q	heat flux, W/m^2
Re	Reynolds number; GD / μ
T	Temperature, ℃
Greek sysbols	
ρ	density of fluid, kg/m^3
μ	dynamic viscosity, Pa·s
△	difference value
Subscripts	
b	bulk
c	critical point
h	heated
pc	pseudo-critical point
i	inlet, inner
o	outlet, outer
w	wall
Abbreviations	
HTD	heat transfer deterioration
HTC	heat transfer coefficient

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REFERENCES

[1] G. Manente, A. Lazzaretto, "Innovative biomass to power conversion systems based on cascaded supercritical CO_2 Brayton cycles," Biomass and Bioenergy, **69**, pp. 155-168 (2014).
[2] K. Ochsner, "Carbon dioxide heat pipe in conjunction with a ground source heat pump (GSHP)," Appliedl Thermal Engineering **28**, pp. 2077-2082 (2008).
[3] R.D. Wood, J.M. Smith, "Heat transfer in the critical region-temperature and velocity profiles in turbulent flow," American Institute of Chemical Engineers Journal, **10**(2), pp. 180-186 (1964).
[4] W.B. Hall, "Heat transfer near the critical point," in: T.F. Irvine, Jr, J.P. Hattnett (Eds.), Advances in Heat transfer, Vol.7, Academic Press, New York, 1971, pp. 1-86.
[5] V.A. Kurganov, A.G. Kaptil'nyi, "Velocity and enthalpy fields and eddy diffusivities in a heated supercritical fluid flow," Experimental Thermal and Fluid science, **5**, pp. 465-478 (1992).
[6] M. Bazargan, M. Mohseni, "The significance of the buffer zone of boundary layer on convective heat transfer to a vertical turbulent flow of a supercritical fluid," Journal of Supercritical Fluids, **51**, pp. 221–229 (2009).
[7] Y.Y. Bae, H.Y. Kim, D.J. Kang, "Forced and mixed convection heat transfer to supercritical CO_2 vertically flowing in a uniformly-heated circular tube," Experimental Thermal and Fluid Science, **34**, pp. 1295-1308 (2010).
[8] Y.Z. Chen, M.F. Zhao, C.S. Yang, K.M. Bi, K.W. Du, "An experimental study of heat transfer in natural circulation of supercritical water," Proceedings of the 9th International Topical Meeting on Nuclear Thermal-Hydraulics, Operation and Safety (NUTHOS-9), Kaohsiung, Taiwan, September 9-13 (2012).
[9] E.A. Krasnoshchekov, V.S. Protopopov, V. Fen, I.V. Kuraeva, "Experimental investigation of heat transfer for carbondioxide in the supercritical region," in: Gazley, Jr., C., Hartnett,J.P., Ecker, E.R.C. (Eds.), Proceedings of the Second All-SovietUnion Conference on Heat and Mass Transfer, Minsk, Belarus, May, 1964, Published as Rand Report R-451-PR, Vol. 1, 1967, pp. 26-35.
[10] J.D. Jackson, "Consideration of the heat transfer properties of supercritical pressure water in connection with the cooling of advanced nuclear reactors," Proceedings of the 13th Pacific Basin Nuclear Conference, Shenzhen City, China, October 21-25 (2002).
[11] S. Mokry, I.L. Pioro, A. Farah, K. King, S. Gupta, W. Peiman, P. Kirillov, "Development of supercritical water heat-transfer correlation for vertical bare tubes," Nuclear Engineering and Desig, 241, pp. 1126-1136 (2011).
[12] S. Gupta, D. McGillivray, P. Surendran, T. Liliana, I. Pioro, "Developing a heat-transfer correlation for supercritical CO_2 flowing in vertical bare tubes," Proceedings of the 2012 20^{th} International Conference on Nuclear Engineering collocated with the ASME 2012 Power Conference (ICONE20-POWER2012), Anaheim, California, USA, July 30-August 3, paper 54626 (2011).
[13] A.A. Bishop, R.O. Sandberg, L.S. Tong, "Forced convection heat transfer to water at near-critical temperatures and supercritical pressures," Report WCAP-2056, Part IV, November, Westinghouse Electric Corporation, Pittsburgh, USA (1964).